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ABSTRACT

The tensile properties and fracture behaviour of two submarine construction steels, BIS 812 EMA and Q1N, have been studied. Their properties and fracture behaviour were measured and observed over a wide range of test temperatures utilizing plain and notched tensile specimens. The yield strength of both materials was found to increase with decreasing temperature and the fracture surface appearance of these steels was also temperature dependent. Under certain conditions "star fracture" was exhibited, rather than the usual cup-and-cone type fracture. The predominance of the "star type fracture" increased with decreasing temperature in both plain and notched tensile specimens, however, it was suppressed by notching. This paper describes the fractographic features of the surfaces and proposes that a range of conditions exist under which "star fracture" occurs in these materials.

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Executive Summary

The tensile properties and fracture behaviour of two submarine construction steels, BIS 812 EMA and Q1N, have been studied over a wide temperature range. The yield strength of both materials was found to increase with decreasing temperature and the fracture surface appearance of these steels was also temperature dependent. Under certain conditions "star fracture" was exhibited and this paper describes the conditions under which "star fracture" occurs in these materials.

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Contents

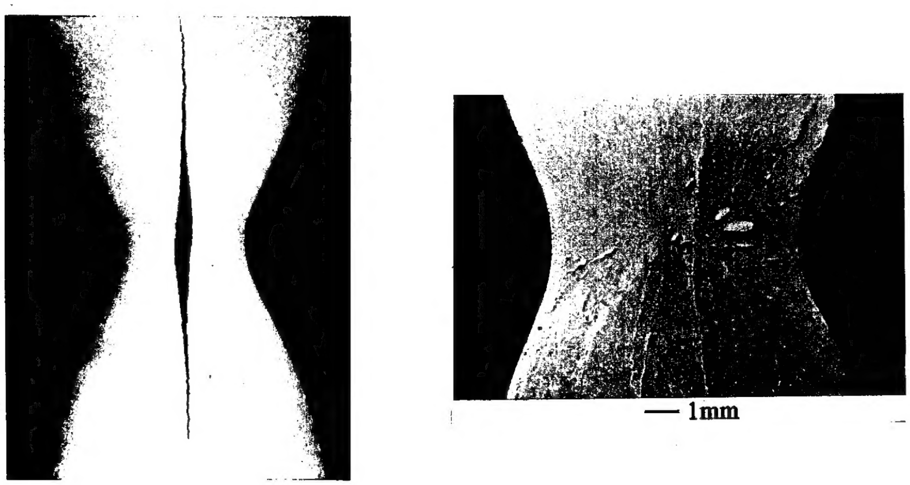
1. Introduction

With the need for higher strength in Naval construction steels, new alloys have been developed which provide the required strength with acceptable welding fabrication properties. These steels fall into two classes, the HY class and the HSLA class.The HY class are high yield strength (550-900 MPa) quenched and tempered steels while the HSLA type receive a thermo-mechanical treatment to attain the desired properties. Of particular interest in the present work are steels designated BIS 812 EMA and Q1N, these steels are similar to the HY class of steel because they have uniform tempered martensitic microstructures whereas the HSLA type steels have precipitation strengthened ferritic microstructures.

BIS 812 EMA is used in the construction of the Collins Class submarine for the Royal Australian Navy and Q1N is a steel originating in the United Kingdom used for submarines and structural members of other maritime structures.

As part of the design process, both the physical and mechanical properties of these materials have been studied extensively. Of particular importance in the development of fracture control technologies are the temperature transition properties which are to some extent determined by the type of test, the test geometry and the loading rate. This paper reports on the temperature transition behaviour of tensile specimens under conditions of increased notch acuity and decreasing test temperatures.

During the tensile testing of the BIS 812 EMA and Q1N steels it was found that some of the fracture surfaces exhibited "star fracture" and/or longitudinal splitting as shown in Figure 1.



(a) (b)

Figure 1. (a) Optical macrograph and (b) Scanning electron micrograph of longitudinal splitting in a plain tensile specimen of BIS 812 EMA steel.

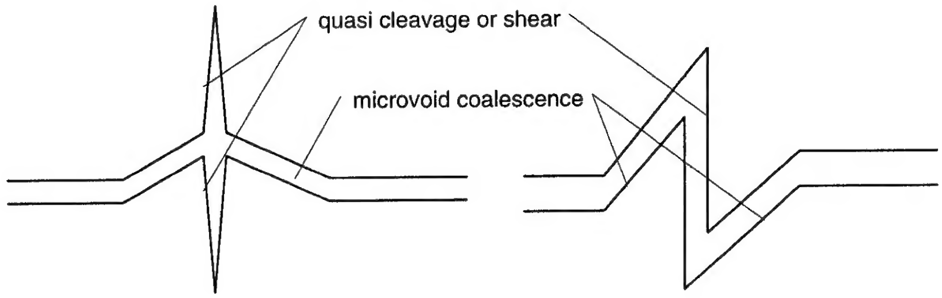
The phenomenon of "star fracture" is well documented [1-3] and is also known as "spoke-shaped fracture" [4], "fraserbruche" or "milling cutter fracture" [5] and "delamination fracture" [6,7]. From these reported studies of fracture behaviour, it is not clear whether "star fracture" and longitudinal splitting (delamination fracture) are variations of the same fracture process or are controlled by competing mechanisms. Although the case for similarity is implied in the literature, it is not clearly demonstrated. Both "star fracture" and longitudinal splitting have been shown to occur prior to final catastrophic failure of plain tensile specimens [1], with the characteristic fracture processes being confined to the region of the neck. In the present work, "star fracture" and longitudinal splitting are treated as two distinct failure modes; but it is likely that they are related and this possibility is investigated. As a general rule, the number of radial fractures decreases as the length of the longitudinal splits increases.

Zok and Embury [6] consider that "longitudinal splitting is not a failure mechanism competing with other mechanisms such as shear lip formation and ductile rupture but rather one which accompanies these failure modes". The propensity for "star fracture" or longitudinal splitting was presented within fracture mechanism maps where failure locii showed initial yield, ultimate tensile strength and the stress trajectories on the effective stress-mean stress plane.

The processes by which the longitudinal fractures occur have not been studied in detail. It has been suggested by Zok and Embury [6] that the process may be the result of cleavage [1], ductile fracture [8,9], grain boundary separation and tearing [10] or temper embrittlement [11]. Zok and Embury [6] also suggest the propensity for longitudinal splitting (in particular) is also influenced by the processing route of the steel, suggesting some microstructural dependence upon the process. Similar associations between longitudinal splitting and banded microstructures have also been made, [12].

"Star fracture" surfaces and to a lesser extent longitudinal splitting fracture surfaces, in tensile specimens are generally characterized by the presence of radially-distributed shear escarpments; with the longitudinal splitting being confined to the necked regions of tensile specimens, as shown in Figure 1, above. Two types of "star fracture" have been reported by Larson and Carr [13], as shown in Figure 2.

In the present context it seems reasonable to associate "star fracture" with Type 2 fracture, see also [11], and longitudinal splitting with Type 1. From the various reported observations of "star fracture" the number of radial fractures and the depth of the longitudinal splitting appear quite variable and may be dependent upon the geometry of the specimen, the temperature of testing and the microstructure of the steel.



Type 1 Radial fracture Type 2 Radial fracture

Figure 2. Detail of two types of radial fracture, after Larson and Carr [13]

The significance of "star fracture" and longitudinal splitting mechanisms in terms of materials performance is somewhat undetermined. For example, the occurance of longitudinal splitting has been associated with reductions in impact energy of a micro-alloyed Ti-V plate steel [7] and a low carbon-Mn steel [8]. Splitting normal to the fracture face has also been observed in the dynamic tear testing of HSLA 80 steel, [14], but the effect of toughness on the degree (or density) of splitting is not known.

"Star fracture" and longitudinal splitting have been shown by some authors to be orientation dependent. For HSLA 100 steel, it has been reported [15] that "star fracture" behaviour is observed for longitudinal and transverse orientations but not for the short transverse orientation. It was suggested that, for HSLA 100 rolled plate, this may be a consequence of the lower elongation and area reduction properties of this orientation, where the conditions for the formation of "star fracture" were not achieved before a cup-and-cone fracture could develop. "Star fracture" was not observed in the transverse tensile specimens of AISI 4340 steel [1], the fact that the more conventional tensile fracture process occur may be related to the cleanliness of the steel.

The temperature dependence on the occurence of "star fracture" and longitudinal splitting has been studied in some detail. For AISI 4340 steel, [1], as the temperature of testing was decreased, the length and number of longitudinal cracks increased. In testing notched tensile specimens of ASTM A710 steel, Hincho et al [2], the longitudinal splitting process was supressed at room temeprature. Hincho et al concluded that both plastic strain (of undetermined level) and a tri-axial stress state were necessary for the formation of longitudinal splits.

From the above review it is considered that the occurance of "star fracture" and longitudinal splitting is not easily explained in terms of any one of the following; test specimen geometry, cleanliness of the steel, composition of the steel, stress state within the neck and work hardening rate. It appears more likely that the occurance of "star fracture" and longitudinal splitting is the result of many competing processes (unlike the suggestions of Zok and Embury [6] discussed above). It may well prove possible to describe the conditions under which these fracture processes will dominate and thereby determine the mechanism for this process.

2. Experimental Procedures

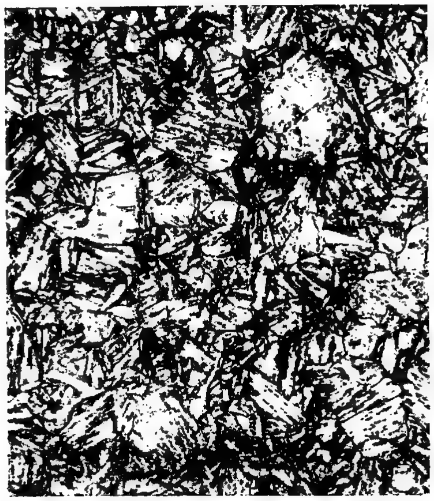
The test materials were commercial submarine plate steels, BIS 812 EMA and Q1N, which were obtained as rolled and heat treated plates. Both steels were supplied as 50 mm thick plate. The composition of the two steels is given in Table 1.

Table 1: Chemical composition of ship plate steels, wt%

	C	Si	Mn	Ni	Cr	Mo	Cu	V	Ti	Nb	Al	S	P	B
BIS 812 EMA (actual heat)	0.13	0.24	0.93	1.28	0.48	0.39	0.21	0.02	0.01	0.01	0.07	0.001	0.011	0.007
Q1N (actual heat)	0.143	0.27	0.34	2.85	1.39	0.40	0.025	0.05	0.007	0.008	0.03	0.001	0.012	-

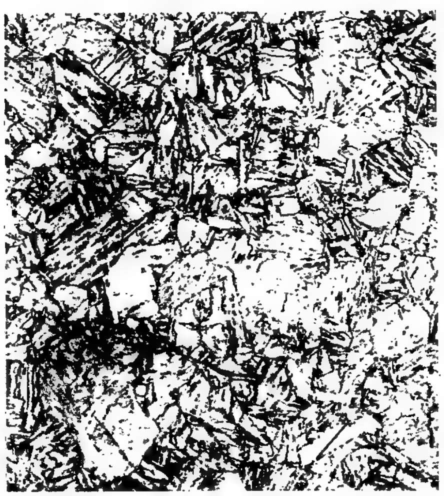
The microstructure of Q1N is similar to that of BIS 812 EMA as shown in Figure 3(a) and (b). One characteristic, common to both steels is the presence of dark etching bands on specimens prepared for metallography, Figures 3(c) and (d). The dark etching bands appear primarily at the central region of the plates aligned with the rolling direction. As the distance away from the centre of the plate increases (in the short transverse direction) the banding becomes lighter and diminishes. The banding is more pronounced in the centre of the Q1N plate (in the short transverse direction) but as the distance away from the centre of the plate increases the diffence in the darkness of the bands in the two steels is not easily discernable.

Tensile specimens were taken from the upper and lower halves of the plates, areas away from the heavier banded microstructures and as such is not expected to have a significant effect on the tensile properties.



(a)

(b)



(c)

(d)

Figure 3. Microstructures of (a) BIS 812 EMA and (b) Q1N steels, optical micrographs of dark etching phases of (c) BIS 812 EMA and (d) Q1N steels. (x250)

The BIS 812 EMA and Q1N steels used in this work have nominal yield strenths of 700 and 550 MPa respectively. Both steels are quenched and tempered to produce fully (tempered) martensitic microstructures.

The tensile test specimens were machined with the long axis in the longitudinal direction. Two types of specimen were used; a plain tensile specimen as shown in Figure 4(a) and a notched tensile specimen as shown in Figure 4(b).

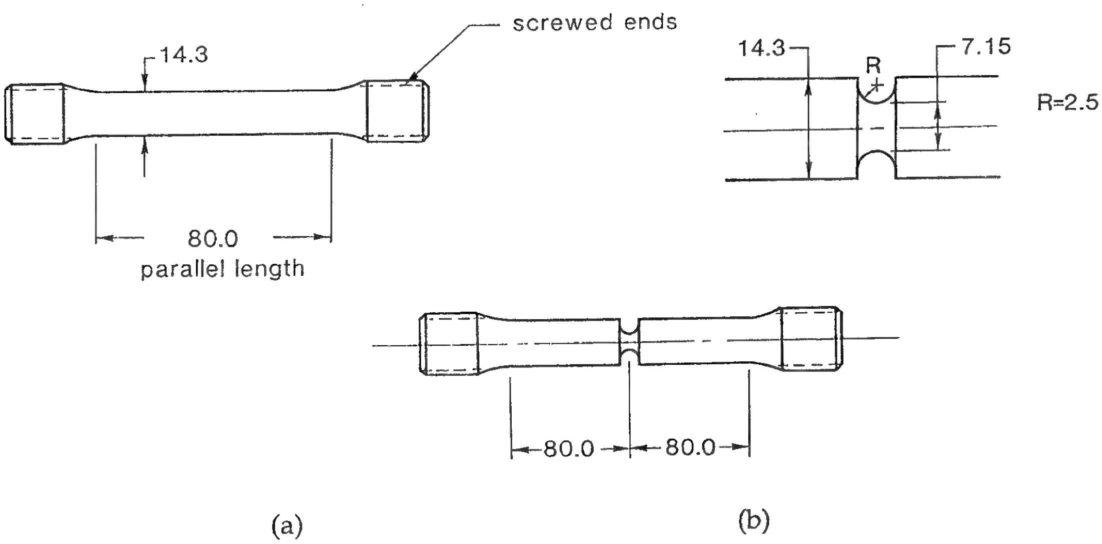


Figure 4. (a) Plain and (b) notched tensile specimens.

The tensile tests were conducted at nominal temperatures of -100°C, -80°C, -60°C, -40°C, -20°C, 0°C and +20°C or room temperature and load displacement records were plotted autographically during each of the tests.

The fracture surfaces of a specimen tested at each temperature were examined under the scanning electron microscope. A notched and un-notched (plain) tensile test piece from each material tested at room temperature and -100°C were sectioned through the fracture surface and examined under an optical microscope.

3. Experimental Results

The tensile and notched tensile properties of BIS 812 EMA and Q1N parent plates are summarized below.

3.1 Tensile Properties

3.1.1 BIS 812 EMA

Summaries of the plain (un-notched) and notched tensile properties for BIS 812 EMA are presented in Figures 5 and 6, respectively.

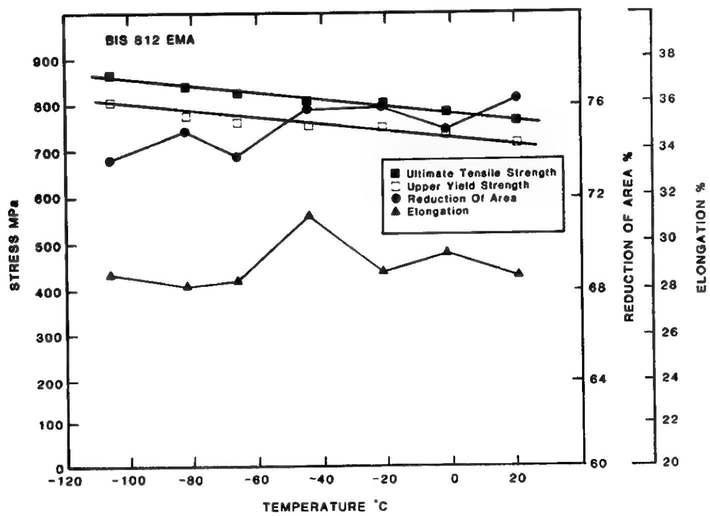


Figure 5. The properties determined from plain tensile specimens of BIS 812 EMA.

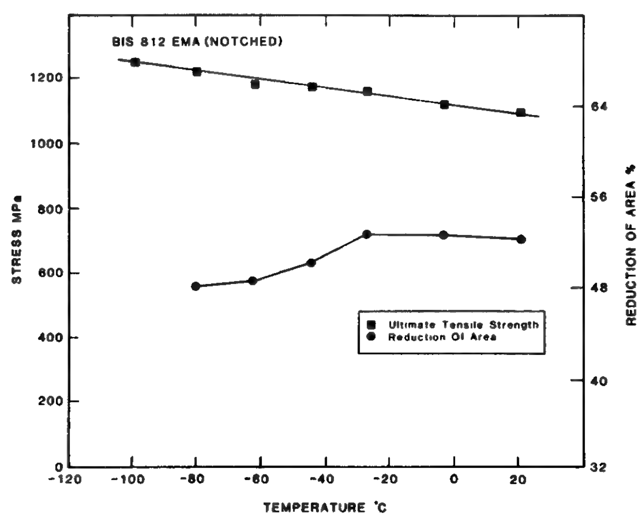


Figure 6. The properties determined from notched tensile specimens of BIS 812 EMA.

The plain tensile specimens of BIS 812 EMA exhibited a pronounced upper and lower yield point as indicated in Figure 5. This was not observed for the notched tensile specimens.

3.1.2 Q1N

Summaries of the recorded plain and notched tensile properties for Q1N are presented in Figures 7 and 8 respectively.

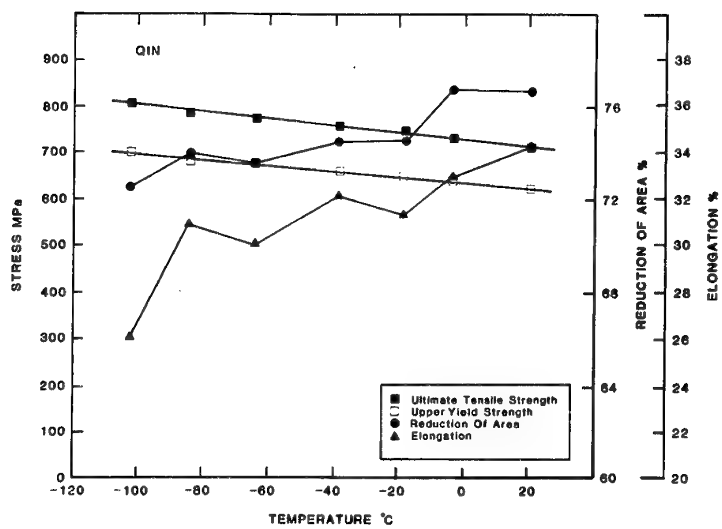


Figure 7. The properties determined from plain tensile specimens of Q1N.

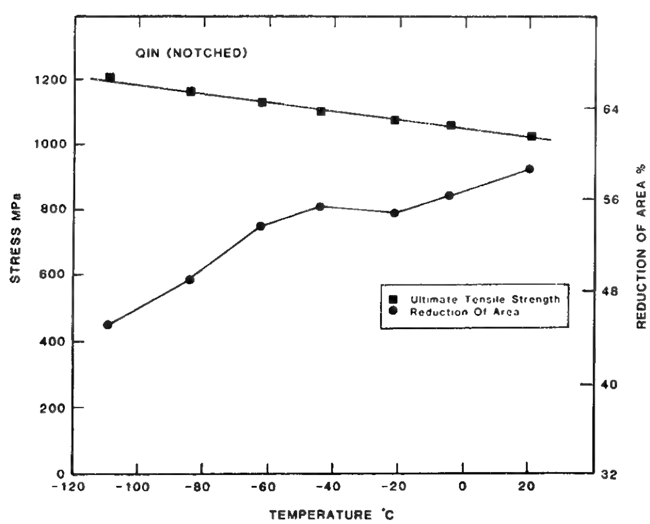


Figure 8. The properties determined from notched tensile specimens of Q1N.

3.2 Fracture Appearance

The types of fracture surfaces obtained in the test program varied according to the type of specimen and the temperature of testing. The trends in the fracture behaviour and fracture surface topography were similar for the BIS 812 EMA and the Q1N steels and are discussed in the sections below using the descriptions of fracture surface topography of Larson and Carr [13].

3.2.1 BIS 812 EMA

Scanning electron micrographs of plain and notched tensile specimens of BIS 812 EMA steel are shown in Figure 9.

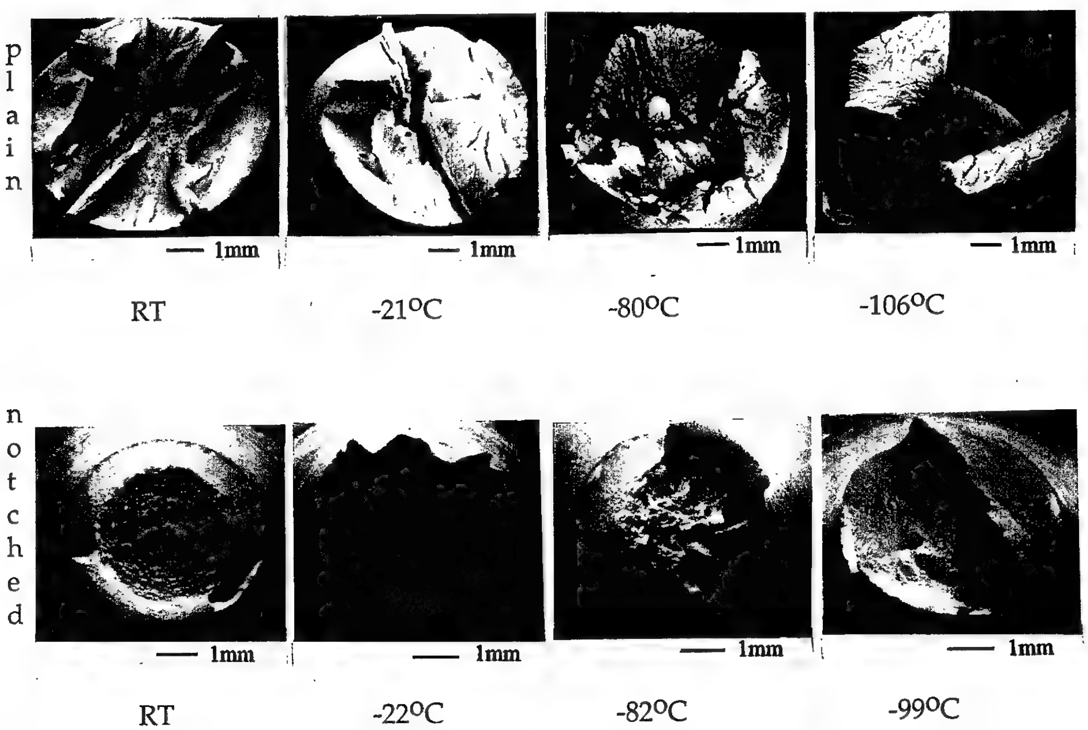


Figure 9. Fracture appearances of plain tensile specimens of BIS 812 EMA (upper) and notched BIS 812 EMA (lower) tested over a range of temperatures. Scanning electron micrographs.

Figure 9 shows the changes in fracture topography with changes in test temperature. Most significantly, "star fracture" was exhibited by the plain tensile specimens over the entire temperature range. The depth of the longitudinal cracking increased as the testing temperature was decreased.

For the plain tensile specimens, at all temperatures, the fracture surfaces normal to the tensile axis (i.e. the regions of "fibrous fracture" [13]) was fine microvoid coalescence as shown in Figure 10.

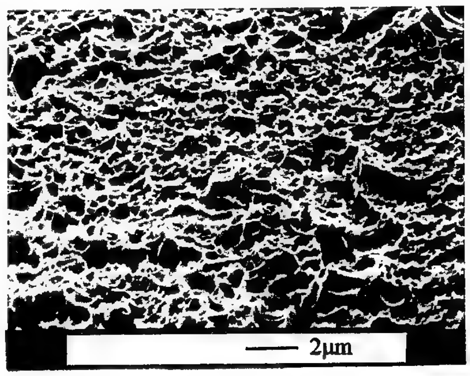
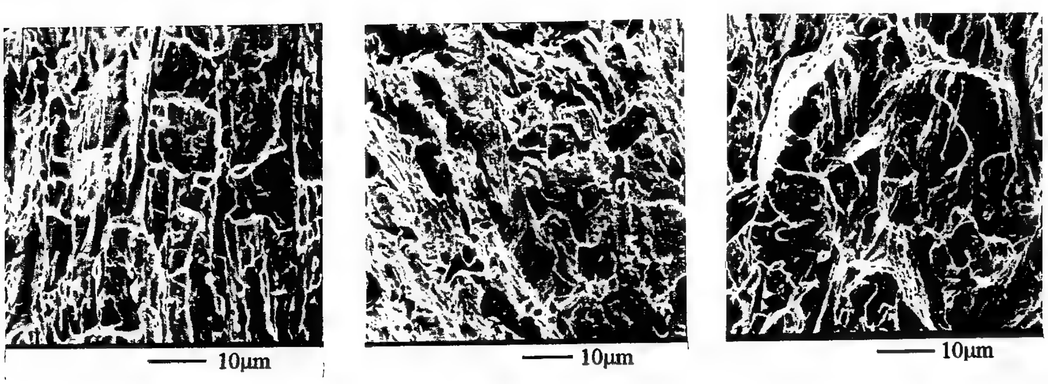


Figure 10. Microvoid coalescence in a plain tensile specimen of BIS 812 EMA tested at room temperature. Scanning electron micrograph.

The longitudinal fractures which constituted the escarpments of the radial fractures ("star fractures") and the longitudinal splits appeared to change in nature depending upon the temperature of testing as shown in Figure 11.



(a) (b) (c)

Figure 11. Fracture surfaces of longitudinal splits from BIS 812 EMA plain tensile specimens. Scanning electron micrographs.

For the plain tensile specimens, at room temperature and down to -62^{o}C, the fracture was largely a ductile shear process, Figure 11(a), and 11(b); at -80^{o}C minor regions of river markings (quasi-cleavage) were in evidence and below -100^{o}C the river markings of a quasi cleavage failure mode became dominant, Figure 11(c). The changes in fracture appearance, observed as testing temperature was decreased suggested a transition in the longitudinal fracture mode.

The notched tensile specimens of BIS 812 EMA exhibited conventional cup-and-cone fractures at room temperature and at temperatures down to -82^{o}C; below this temperature the cup-and-cone fractures were largely replaced by "star fracture" and longitudinal splitting. "Star fracture" facets were formed concurrently with the cup-and-cone fractures at -63 and -82^{o}C and longitudinal splitting the dominant fracture mode below -82^{o}C.

As observed in the plain tensile specimens, the fibrous region of the notched tensile specimens consisted of fine microvoid coalescence. The radial escarpments of the specimen tested at -63^{o}C exhibited a quasi cleavage fracture surface, but with appreciable deformation. The escarpments at -99^{o}C exhibited "classical" quasi cleavage fracture surfaces. The fracture mode did not exhibit the transition from ductile shear to quasi cleavage exhibited by the plain tensile specimens as described above.

As a general trend for both the plain and notched tensile specimens, the number of "star fracture" facets and the length of longitudinal splitting from the "star fracture" facets increased as temperature was decreased. Notching, however, suppressed the formation of "star fracture" and longitudinal splitting.

3.2.2 Q1N

The fracture behaviour observed for the Q1N was similar to that observed for the BIS 812 EMA steel. Typical fracture behaviour over a range of temperatures is shown in Figure 12.

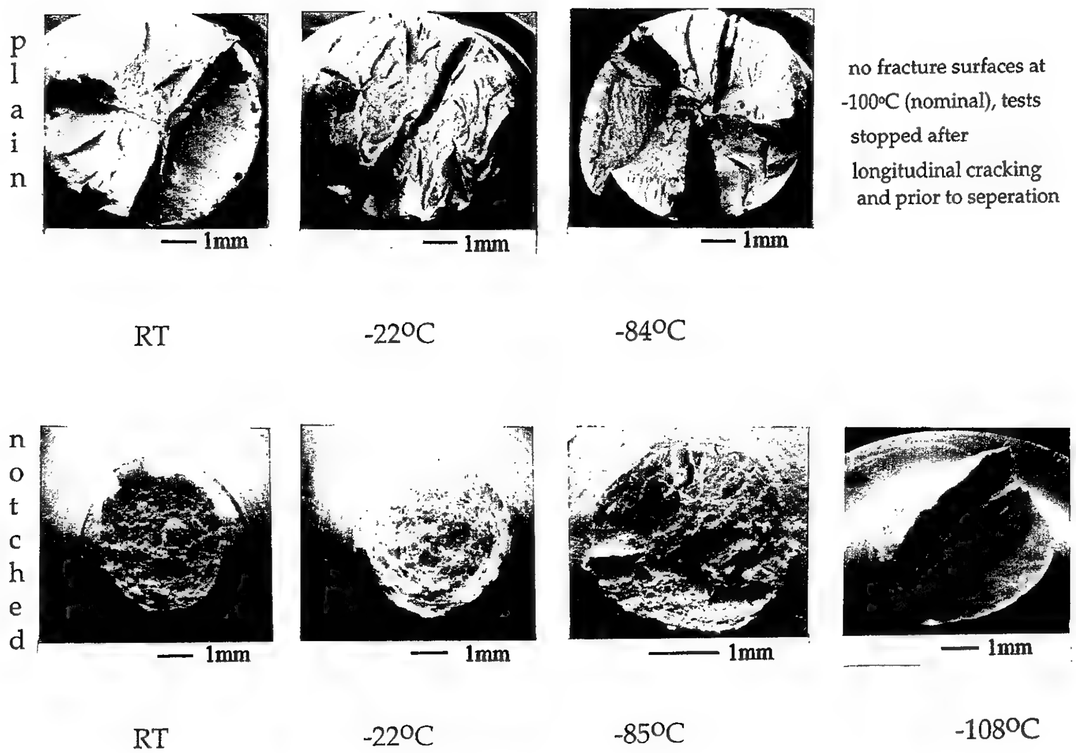


Figure 12. Fracture appearances of plain tensile specimens of Q1N (upper) and notched tensile specimens of Q1N (lower) tested over a range of temperatures. Scanning electron micrographs.

The general fracture appearances of the longitudinal splits shows a similar transition to that observed for the BIS 812 EMA steel. For example, Figure 13 shows the fracture surfaces of longitudinal splitting in plain tensile specimens over a range of temperatures.

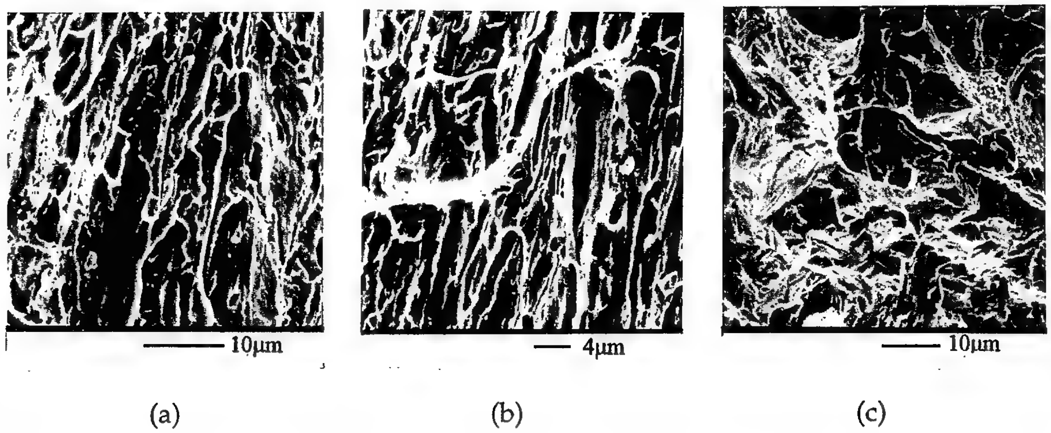


Figure 13. Fracture surfaces of longitudinal splitting in plain tensile specimens of Q1N steel. Scanning electron micrographs.

3.3 Optical Microscopy

Preparation of samples for optical microsopy consisted of sectioning the tensile specimens through the necked regions revealing the profiles of the longitudinal splits, "star fractures" or cup and cone failures. Samples were taken from plain and notched specimens tested at approximately -100°C (nominal) and at room temperature from both BIS 812 EMA and Q1N steels. The type of tensile test failure was similar for each material of the same geometry and at the same temperature.

Examination of the plain tensile specimens showed that at room temperature and -100°C (nominal), longitudinal splitting occurred accompanied by substantial void formation, Figures 14 and 15.

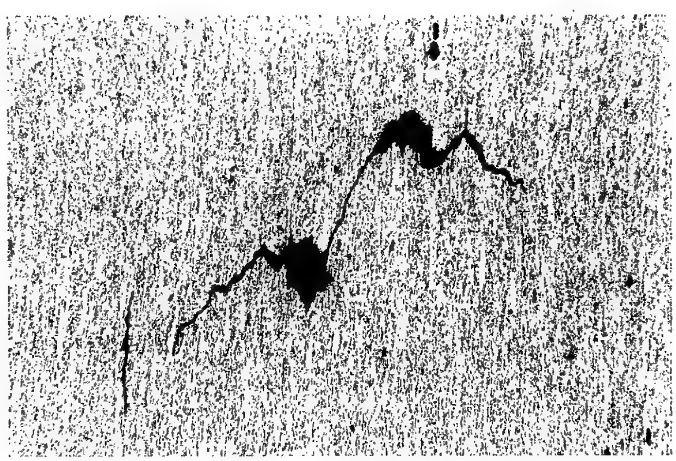


Figure 14. Void formation and longitudinal splitting within the neck of a plain tensile specimen of Q1N steel tested at -98°C. Specimen testing was stopped just prior to failure. (x75)

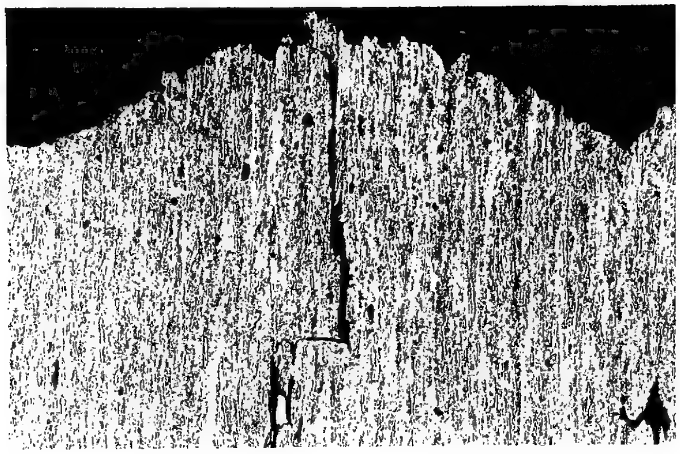


Figure 15. Longitudinal splitting within the neck of a plain tensile specimen of BIS 812 EMA steel tested at room temperature. (x100)

For notched tensile specimens of BIS 812 EMA tested at -100^{o}C (nominal), "star fracture" was the fracture mode and optical microscopy revealed some void formation within the notched region, Figure 16.

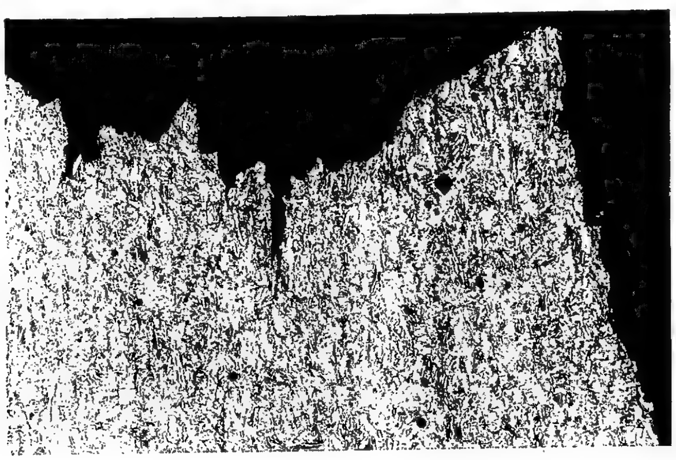


Figure 16. Longitudinal splitting within the neck of a notched tensile specimen of BIS 812 EMA steel tested at -108^{o}C. (x100).

The room temperature test resulted in cup and cone failure and void formation in the region of fibrous fracture, Figure 17.

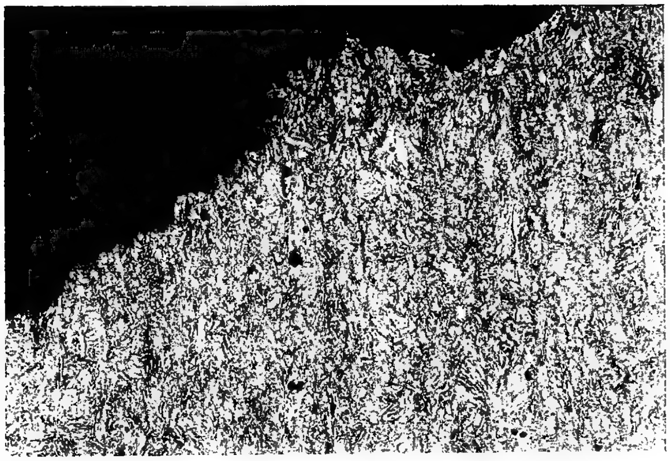


Figure 17. Void formation within the fibrous region of the neck in a notched tensile specimen of BIS 812 EMA steel tested at room temperature. (x100)

From the present experiments it appears that, as the temperature decreases and/or notch severity decreases, void formation is suppressed and the fracture appearance moves away from cup and cone to "star fracture" and finally longitudinal splitting, ie from fibrous (cup and cone), to Type 2 and then to Type 1 radial fracture. For the two steels studied in the present work, Type 1 radial fracture appeared to be associated with a brittle fracture process (i.e. quasi cleavage).

3.4 Electron Probe Micro-Analysis

Electron probe micro-analysis of BIS 812 EMA steel was carried out to determine if the dark etching bands, observed by optical microscopy, contained significant variations in chemical composition that might have some influence on the presence of "star fracture" or longitudinal splitting. Typical longitudinal splitting is shown in Figure 18.

The micro analysis of the dark etching bands determined nickel, manganese, chromium, molybdenum and silicon contents and the results of microprobe scans across one of these bands show some variations in compostion. Most variation occured with nickel and manganese concentrations. The change in composition of the nickel content varied by approximately 0.3% and the manganese content by approximately 0.3%. This was significantly less than reported for banding in other similar steels, [15]. The chromium, molybdenum and silicon concentrations showed little variation across the bands. With deformation of the necked region, the bands become significantly elongated and fine. However, no consistant location of splitting within these bands could be established. Similarly, in the notched tensile specimens, where the microstructure (including the bands) was significantly less deformed, longitudinal fracture was not consistantly associated with either the dark etching bands or the regions of lighter etching.

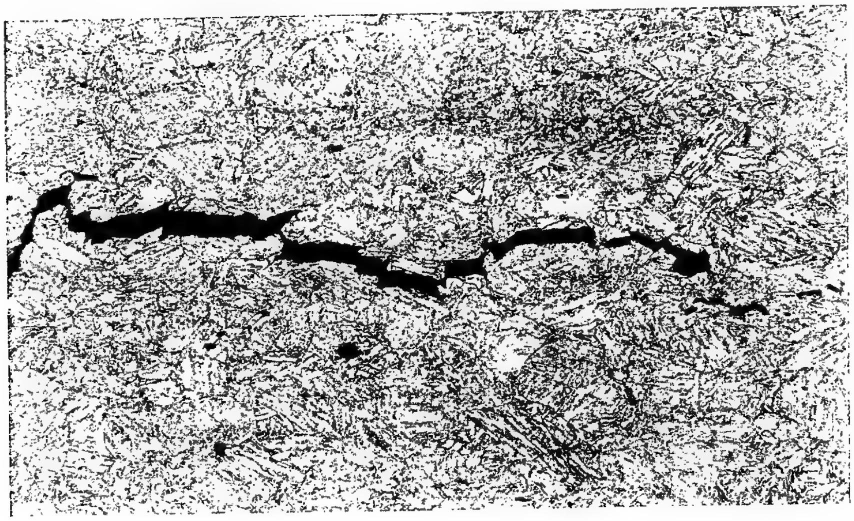


Figure 18. Longitudinal splitting and dark etching bands in BIS 812 EMA tested at -100^{o}C. (x250).

4. Discussion

The work has shown that the fracture processes within tensile specimens of BIS 812 EMA and Q1N steels produce several different fracture surfaces depending upon the testing conditions and the presence of notches.

It was found that, for the plain tensile specimens of both BIS 812 EMA and Q1N, there was not a significant region of fibrous fracture at room temperature. Significant "star fracture" and longitudinal splitting, however, occurred over the entire temperature range studied with the deepest splitting occuring at the lowest temperature. The progression of the fracture behaviour is shown schematically in Figure 19.

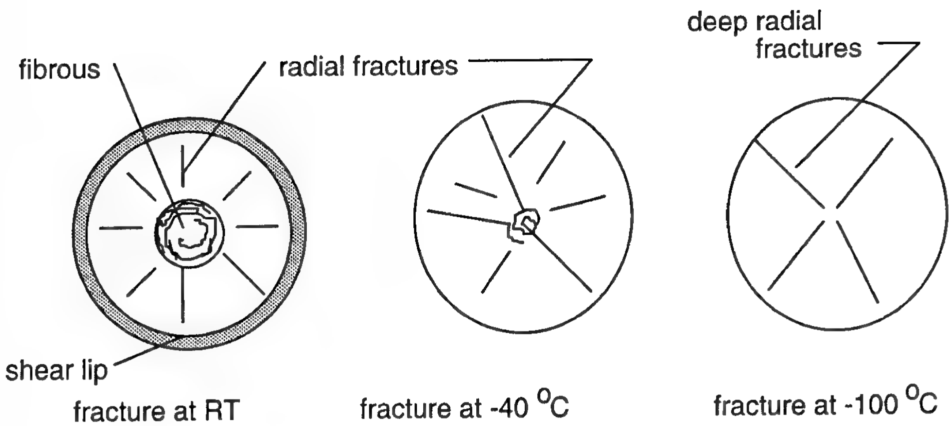


Figure 19. Fracture progression in plain tensile specimens, after Larson and Carr [13].

In the case of the notched tensile specimens the fracture progression is shown schematically in Figure 20.

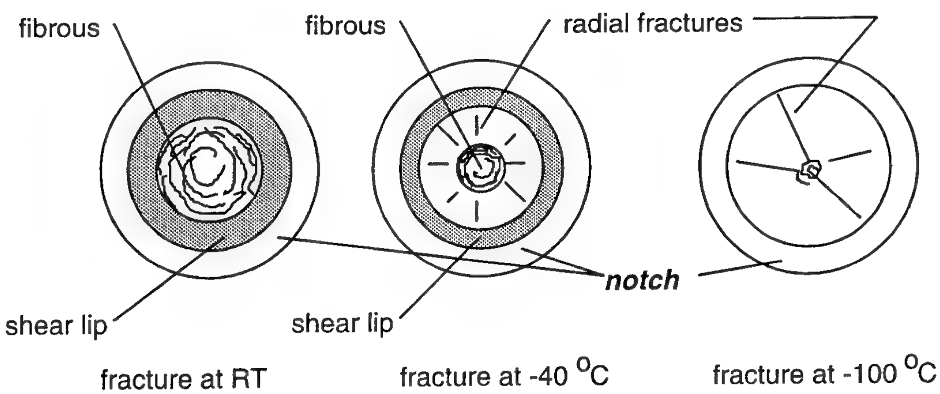


Figure 20. Fracture progression in notched tensile specimens, after Larson and Carr [13].

In all specimens the regions of fibrous fracture were composed of circumferential ridges about the mid point of the specimen; this suggests uniform crack growth from a nucleation point at the centre of the specimen [16,11]. Hancock and Mackenzie [17] studied the nucleation and growth of cracks in notched Q1N and HY130 steels and showed that large cracks formed across the central sections of the test specimens, normal to the tensile axis. These cracks were the result of the linking of small voids nucleated at inclusions early in the strain histories of the specimens. The linking process was associated with the load drop in the tensile stress-strain records. Shtremel' et al [11] claimed that this observation was in accord with the models of ductile fracture of McClintock [18] and Thomason [19]. In the present work, where fibrous

fracture was exhibited in both the BIS 812 EMA and Q1N steels, the dimples were generally nucleated by small MnS inclusions, however, the MnS inclusions were significantly larger and more prevalent in the Q1N steel resulting in larger dimples within the fibrous region of this steel, as seen by comparing Figures 9 and 12.

For the purpose of this discussion it will be assumed, initially, that "star fracture" and longitudinal splitting are two distinct fracture processes. This initial assumption is somewhat justified by the observation that they follow a consistant progression with temperature and notching, with Type 1 radial fracture becoming predominant over Type 2 as the temperature is lowered, as shown in Figures 19 and 20. This is not the impression gained from the literature where most authors consider "star fracture" and longitudinal splitting to be the same process.

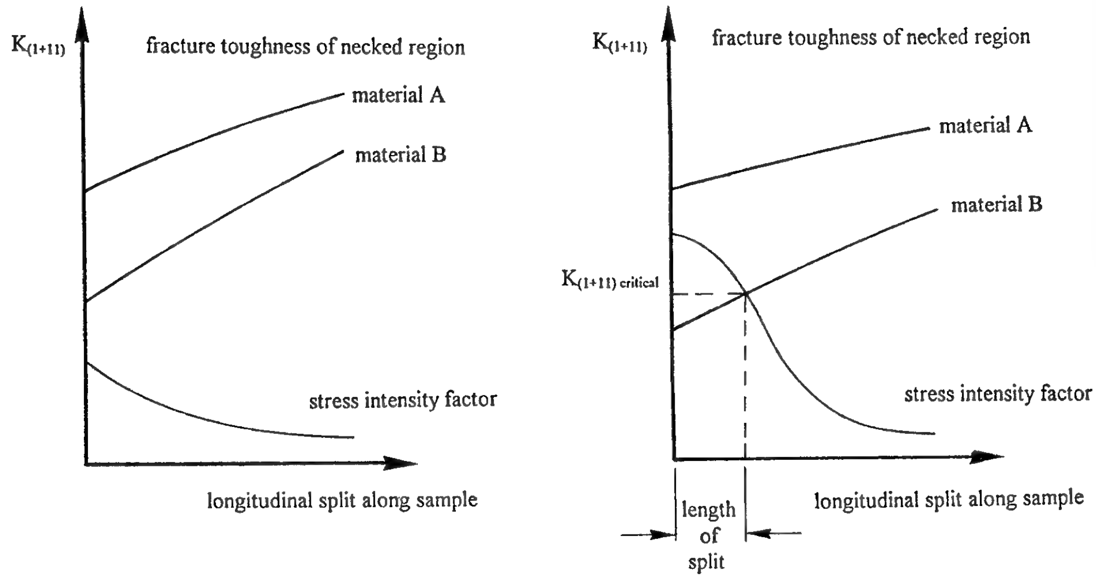
Most significantly, both radial fracture processes appear to rely upon the development of a neck within the specimen. The process is suppressed, however, by the introduction of a notch and by increasing the test temperature, as seen in Figures 9 and 12. Additionally, longitudinal splitting does not appear to be associated with the banding observed in these steels, although the splitting process has been associated with banding in other steels of higher manganese content. Where banding is significant in steels it has the same effect as the highly deformed regions within the necks of tensile specimens, thereby providing a microstructure of low fracture toughness. In the present work, the non-association with banding is reinforced by the observations that longitudinal splitting also occurs in transverse tensile specimens of BIS 812 EMA and Q1N, [20]. The scanning electron microscopy of the longitudinal splits in Q1N has indicated the existance of the fibrous fracture mode prior to the formation of the longitudinal splits, see Figure 13. The formation of longitudinal splits, then, appears dependent upon the generation of the appropriate conditions within the specimen which may follow the initial development of fibrous fracture within the central necked portion of the specimen. The longitudinal splitting observed in the BIS 812 EMA and the Q1N steels is consistent with the mechanism of longitudinal splitting proposed by Zok and Embury [6]. Zok and Embury suggest that "the distribution of delamination events strongly suggest that the planes of delamination depend upon events which occur during the test rather than being pre-existing planes of weakness due to prior processing", see also Shtremel' et al [11]. The distribution of carbides and sulphides, however, can aid the fracture process [15], by creating conditions conducive to a preferential failure mode. In the case of the BIS 812 EMA and the Q1N steels studied here, the conditions for longitudinal splitting are low temperatures and significant necking which results in enhanced circumferential stresses. Some consideration also needs to be given to the apparent change in fracture process from ductile shear to quasi-cleavage at low temperatures exhibited by both the BIS 812 EMA and the Q1N steels. The fracture surfaces of the longitudinal splits derive from highly deformed material, to produce the ductile shear fracture at most temperatures and a cleavage fracture at low temperatures. Quasi cleavage is more easily identified in the notched tensile specimens where significantly less deformation had occurred. Once longitudinal cracking is initiated, cracks will continue to propagate until the arrest (or dynamic) stress intensity factor exceeds the stress intensity factor at the crack tip. As the temperature is lowered, the arrest (or dynamic) fracture toughness of the steels are also lowered, [21]. It would appear that, since both BIS 812 EMA and Q1N steels

exhibit very small changes in ductility over the temperature ranges studied, the extent (length) of longitudinal cracking is more significantly influenced by toughness than by geometry changes at the neck.

The formation of "star fractures" is consistent with the fractographic work reported on ASTM A710 steel [2] and ASTM A490 high strength steel bolts [17]. "Star fractures" were reported to be favoured by high ductility; the formation of these fractures was suppressed by deep notching. It is considered [13,17] that the zone of radial fracture results from unstable or rapid crack growth where the marks trace the direction of crack growth from the edge of the fibrous zone or from some origin within the ligament. The explanation for the formation of the radial cracks given by Larson and Carr [13] in which the collapse of the plastic zone ahead of the crack in the fibrous region will result in the development a tangential stress is not convincing in the light of present experimental evidence and the numerical analyses of the stress states within the necked regions of tensile specimens [17,19]. The experimental evidence is more in accord with the nucleation of radial cracks ahead of a crack propagating around the ligament remaining after fibrous crack growth; the stresses for the opening of these cracks are the hoop stresses developed as a result of the curvature of the neck [17]. This fracture process would be favoured by an unsymmetrical distribution of hoop and axial stresses generated by the nucleation of a short longitudinal crack off the major axis of the neck. Isolated radial cracks are in evidence on some fracture surfaces in the BIS 812 EMA and the Q1N notched tensile specimens. The occurance of this process for "star fracture" is supported by the observations of Shtremel' et al [11] where two possible fracture behaviours (fibrous or "star" and longitudinal splitting) are determined by the conditions for neck formation (in this work there was no differentiation between "star fracture" and longitudinal fracture). Fibrous fractures are induced by conditions of low work hardening while high work hardening rates and anisotropic fracture resistance promote longitudinal cracking. Anisotropic fracture resistance can be the result of many processes : heat treatment (including temper embrittlement [6,10,11]), the re-alignment of fracture nucleating particles [6] and low temperature transition to cleavage or quasi cleavage behaviour as has been demonstrated in the present work.

Whether, as has been initially assumed by the authors, the processes of "star fracture" and longitudinal splitting are competing fracture processes or are basically the same fracture processs has not been clearly resolved by this work. The fractographic evidence suggets that it is likely that there are three competing events; the nucleation of uniform crack growth from inclusions (fibrous fracture), the nucleation of longitudinal cracking and the arrest of propagating longitudinal cracks (which can be a geometry and temperature dependent effect).

It is possible to represent these competing processes schematically, as shown in Figure 21.



(a) (b)

Figure 21. Schematic representation of longitudinal splitting in (a) plain and (b) notched tensile specimens.

The above figure shows the conditions which are necessary for the formation of longitudinal splits in ductile material. The stress intensity factor for an axial split is as yet undetermined, but it is considered that it would be a function of the distance along the neck, l, and related to the three principal stresses within the neck:

$$K_{(I + II)} = F(\sigma_{\theta}, \sigma_{zz}, \sigma_{r}, l)$$

where:

$K_{(I + II)}$ is a mixed mode stress intensity factor
$\sigma_{\theta}, \sigma_{zz}, \sigma_{r}$ are the hoop, axial and radial stresses in the necked region
l = distance along the neck

Two toughness levels (A and B) are plotted in this diagram and cover material in specimens which are necked and un-necked. Considering the un-necked material first, the mixed mode stress intensity factor at hypothetical longitudinal cracks is extremely small, longitudinal splitting does not occur, even with material of toughness level B. For material which has necked, the toughness of the material in the region of necking is below the stress intensity factor and splitting will occur, the crack growing a distance along the neck until the toughness exceeds the stress intensity factor, this occurs for

material of toughness level B. The fracture toughness planes are shown as dipping within the necked region, this behaviour is believed to occur by rearrangement of the microstructure due to the necking process, as proposed by Zok and Embury [6]. The proposed downward curvature of the fracture toughness surfaces in Figure 21 also explains why specimens with machined notches do not exhibit longitudinal splitting for material of the same mechanical properties. The material does not deform to create a microstructure which is of low toughness, the low toughness state can only be achieved by higher deformation levels or lower temperatures as shown by the present work. Where the geometry of the necked regions are similar, the length of splitting is possibly related to the crack arrest properties of the material.

Longitudinal splitting, and "star fracture" do not necessarily represent a materials problem. The process occurs ***because of*** high ductility where large hoop and radial stresses develop within the neck of tensile specimens ***and*** the high level of plastic deformation which creates regions of low toughness within the necked region.

5. Conclusions

The tensile properties of two high strength, low alloys steels have been studied over a wide range of temperatures using plain and notched specimens.

From the test program it can be concluded that:

(1) The tensile properties of the plain specimens of BIS 812 EMA and Q1N showed only minor increases with decreasing temperature to -100^{o}C (nominal). Similar small changes in the notched tensile specimens were exhibited by the BIS 812 EMA and the Q1N.

(2) Fibrous fracture, "star fracture" and longitudinal splitting are competing processes which are dependent upon both the stress-state within the neck of the specimen and the microstructure of the material.

(3) Type 1 fracture or longitudinal splitting becomes more predominant as the temperature of testing is reduced such that the material fails by quasi cleavage.

(4) "Star fracture" and longitudinal splitting processes are enhanced by the formation of the neck and by the creation of longitudinal regions of reduced fracture toughness.

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Observations of star fracture and longitudinal splitting in BIS 812 EMA and Q1N submarine construction steels

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ABSTRACT

The tensile properties and fracture behaviour of two submarine construction steels, BIS 812 EMA and Q1N, have been studied. Their properties and fracture behaviour were measured over a wide range of test temperatures utilizing plain and notched tensile specimens. The yield strength of both materials was found to increase with decreasing temperature and the fracture surface appearance of these steels was also temperature dependent. Under certain conditions "star fracture" was exhibited, rather than the usual cup-and-cone type fracture. The predominance of the "star type fracture" increased with decreasing temperature in both plain and notched tensile specimens, however, it was suppressed by notching. This paper describes in detail the fractographic features of the surfaces and proposes that a range of conditions exist under which "star fracture" occurs in these materials.

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